SOAP – Spherical Overdensity and Aperture Processor

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1 Introduction

SOAP computes different types of properties, depending on how particles are included (by radius, in projection...). For all types, we use the halo membership and centre of potential as determined by the input halo catalogue. This documentation is generated using the SOAP parameter file, and so the properties listed reflect those present in the current run of SOAP, rather than all possible properties.

2 Property types

Subhalo quantities (SH) are computed for each subhalo identified by the halo finder, irrespective of whether it is a field halo or a satellite (or even satellite of satellite and so on). They include all particles that they halo finder has determined are bound to the subhalo. Subhalo properties are contained within the group `BoundSubhalo` in the output file.

Exclusive sphere quantities (ES) are similar to subhalo quantities, but they include only the particles that are bound to the subhalo, and apply an additional radial cut (aperture). We use eight different aperture radii (10, 30, 50, 100, 300, 500, 1000, 3000 kpc), so that every (sub-)halo has eight of these. Exclusive sphere properties are contained within a group `ExclusiveSphere/XXXkpc`, where `XXX` is the corresponding aperture radius.

Inclusive sphere quantities (IS) use the same physical aperture radii as the exclusive sphere quantities, but include all particles within the radius, regardless of their membership status. They are stored within a group `InclusiveSphere/XXXkpc`.

Exclusive projected quantities (EP) are similar to exclusive sphere quantities, except that their aperture filter is applied in projection, and this for independent projections along the x-, y- and z-axis. Along the projection axis, we do not apply any radial cut, so that the depth corresponds to all particles bound to the (sub-)halo. With four projected aperture radii (10, 30, 50, 100 kpc), we then have twelve sets of projected aperture quantities for each (sub-)halo. Projected aperture quantities are stored in a group named `ProjectedAperture/XXXkpc/projP`, where `XXX` is the corresponding aperture radius, and `P` corresponds to a particular projection direction (`x`, `y` or `z`).

Spherical overdensity properties (SO) are fundamentally different from the three other types in that their aperture radius is determined from the density profile and is different for different halos. They always include all particles within a sphere around the centre of potential, regardless of halo membership. The radius is either the radius at which the density reaches a certain target value (50 crit, 100 crit, 200 crit, 500 crit, 1000 crit, 2500 crit, 200 mean, BN98) or a multiple of such a radius (5xR 500 crit). Details of the spherical overdensity calculation are given at the end of this document. Spherical overdensities are only computed for centrals, i.e. field halos. The inclusive sphere quantities are stored in a group `SO/XXX`, where `XXX` can be either `XXX_mean` for density multiples of the mean density, `XXX_crit` for density multiples of the critical density, `BN98` for the overdensity definition of Bryan & Norman (1998), and `YxR_XXX_ZZZ` for multiples of some other radius (e.g. `5xR_2500_mean`). The latter can only be computed after the corresponding density multiple SO radius has been computed. This is achieved by ordering the calculations.

InputHalos Some properties are directly copied from the original halo catalogue that was passed to SOAP. These are stored in a separate group, `InputHalos`.

SOAP Some properties are computed by SOAP using the other halo properties present in the catalogue. These are stored in a separate group, `SOAP`. This is just done for convenience; these quantities can be computed from the SOAP output alone.

The table below lists all the groups in the output file which containing datasets. Note that there will be three groups (`x`, `y` or `z`) for each `ProjectedAperture` variation. Each halo variation can have a filter applied to it. If a halo does not satisfy the filter then the variation will not be calculated for that halo. More information on filters can be found in the next section.

Group name (HDF5)	Group name (swiftsimio)	Inclusive?	Filter
`BoundSubhalo`	`bound_subhalo`	×	-
`SO/200_crit`	`spherical_overdensity_200_crit`	✓	-
`SO/50_crit`	`spherical_overdensity_50_crit`	✓	general
`SO/100_crit`	`spherical_overdensity_100_crit`	✓	general
`SO/200_mean`	`spherical_overdensity_200_mean`	✓	-
`SO/500_crit`	`spherical_overdensity_500_crit`	✓	-
`SO/5xR_500_crit`	`spherical_overdensity_5xr_500_crit`	✓	general
`SO/1000_crit`	`spherical_overdensity_1000_crit`	✓	general
`SO/2500_crit`	`spherical_overdensity_2500_crit`	✓	general
`SO/BN98`	`spherical_overdensity_bn98`	✓	general
`ExclusiveSphere/10kpc`	`exclusive_sphere_10kpc`	×	-
`ExclusiveSphere/30kpc`	`exclusive_sphere_30kpc`	×	-
`ExclusiveSphere/50kpc`	`exclusive_sphere_50kpc`	×	-
`ExclusiveSphere/100kpc`	`exclusive_sphere_100kpc`	×	-
`ExclusiveSphere/300kpc`	`exclusive_sphere_300kpc`	×	-
`ExclusiveSphere/500kpc`	`exclusive_sphere_500kpc`	×	general
`ExclusiveSphere/1000kpc`	`exclusive_sphere_1000kpc`	×	general
`ExclusiveSphere/3000kpc`	`exclusive_sphere_3000kpc`	×	general
`InclusiveSphere/10kpc`	`inclusive_sphere_10kpc`	✓	-
`InclusiveSphere/30kpc`	`inclusive_sphere_30kpc`	✓	-
`InclusiveSphere/50kpc`	`inclusive_sphere_50kpc`	✓	-
`InclusiveSphere/100kpc`	`inclusive_sphere_100kpc`	✓	-
`InclusiveSphere/300kpc`	`inclusive_sphere_300kpc`	✓	-
`InclusiveSphere/500kpc`	`inclusive_sphere_500kpc`	✓	general
`InclusiveSphere/1000kpc`	`inclusive_sphere_1000kpc`	✓	general
`InclusiveSphere/3000kpc`	`inclusive_sphere_3000kpc`	✓	general
`ProjectedAperture/10kpc/projP`	`projected_aperture_10kpc_projP`	×	general
`ProjectedAperture/30kpc/projP`	`projected_aperture_30kpc_projP`	×	general
`ProjectedAperture/50kpc/projP`	`projected_aperture_50kpc_projP`	×	general
`ProjectedAperture/100kpc/projP`	`projected_aperture_100kpc_projP`	×	general
`SOAP`	`soap`	-	-
`InputHalos`	`input_halos`	-	-
`InputHalos/HBTplus`	`input_halos_hbtplus`	-	-
`InputHalos/FOF`	`input_halos_fof`	-	-

3 Property categories

Halo properties only make sense if the subhalo contains sufficient particles. Halo finders are often run with a configuration that requires at least 20 particles for a satellite subhalo. However, even for those particle numbers, a lot of the properties computed by SOAP will be zero (e.g. the gas mass within a 10 kpc aperture), or have values that are outliers compared to the full halo population because of undersampling. We can save a lot of disk space by filtering these out by applying appropriate cuts. Filtering means setting the value of the property to `NaN`; HDF5 file compression then very effectively reduces the data storage required to store these properties, while the size of the arrays that the end user sees remains unchanged. Evidently, we can also save on computing time by not computing properties that are filtered out.

Since different properties can have very different requirements, filtering is done in categories, where each category corresponds to a set of quantities that are filtered using the same criterion. Inclusive, exclusive or projected quantities with different aperture radii (or overdensity criteria) can be used to create profiles. In order for these profiles to make sense, we have to apply a consistent cut across all the different aperture radii (or overdensity criteria) for the same subhalo property type. Or in other words: the quantities for an inclusive sphere with a 10 kpc aperture radius will use the same filter mask as the quantities of the inclusive sphere with a 3000 kpc aperture radius, even though the latter by construction has many more particles.

Basic quantities (basic) are never filtered out, and hence are calculated for all objects in the input halo catalogue.

General quantities (general) use a filter based on the total number of particles bound to the subhalo.

Gas quantities (gas) use a filter based on the number of gas particles bound to the subhalo.

DM quantities (dm) use a filter based on the number of DM particles bound to the subhalo.

Stellar quantities (star) use a filter based on the number of star particles bound to the subhalo.

Baryon quantities (baryon) use a filter based on the number of gas and star particles bound to the subhalo.

Note that there are no quantities that use a BH or neutrino particle number filter.

The particle number thresholds are set in the parameter file. The different categories are summarised in the table below.

Name	criterion
basic	(all halos)
general	$N_{\rm gas} + N_{\rm dm} + N_{\rm star} + N_{\rm BH} \geq 100$
gas	$N_{\rm gas} \geq 100$
dm	$N_{\rm dm} \geq 100$
star	$N_{\rm star} \geq 100$
baryon	$N_{\rm gas} + N_{\rm star} \geq 100$

4 Overview table

The table below lists all the properties that are computed by SOAP when run in HYDRO mode. For dark matter only (DMO) mode only the properties colored violet/purple are computed. This table is automatically generated by SOAP from the source code, so that all names, types, units, categories and descriptions match what is actually used and output by SOAP. For each quantity, the table indicates for which halo types the property is computed. Superscript numbers refer to more detailed explanations for some of the properties and match the numbers in the next section. If swiftsimio has been used to load a catalogue then the fields names are in snake_case rather than CamelCase, e.g. `CentreOfMass` becomes `centre_of_mass`.

Note that quantities are given in the base units of the simulation snapshot. The attributes of each SOAP dataset contains all the relevant meta-data to convert between physical and co-moving units, i.e. information about how the quantity depends on the scale-factor, and what the conversion factor to and from CGS units is. All quantities are h-free. The conversion of the base units to CGS is given by:

Unit	CGS conversion
L	3.086e+24 cm
M	1.988e+43 g
t	3.086e+19 s
T	1 K

For example, a property whose units are listed as M/t will have units of velocity, where $1\,\mathrm{M/t} = 1\,\mathrm{km/s}$. The scale factor is explicitly included for comoving properties (e.g. the units of HaloCentre are aL)

Name	Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
BlackHolesDynamicalMass	Total BH dynamical mass.	1	float32	M	✓	✓	✓	✓	✓	basic	1.36693e10 → 1.367e10
BlackHolesSubgridMass	Total BH subgrid mass.	1	float32	M	✓	✓	✓	✓	✓	basic	1.36693e10 → 1.367e10
CentreOfMass[1]	Centre of mass.	3	float64	$a \cdot L$	✓	✓	✓	✓	✓	basic	1 pc accurate
CentreOfMassVelocity[1]	Centre of mass velocity.	3	float32	$a \cdot L/t$	✓	✓	✓	✓	✓	basic	0.1 km/s accurate
Concentration[2]	Halo concentration assuming an NFW profile. Minimum particle radius set to softening length	1	float32	dimensionless	×	×	×	×	✓	basic	1.36693e10 → 1.367e10
ConcentrationUnsoftened	Halo concentration assuming an NFW profile. No particle softening.	1	float32	dimensionless	×	×	×	×	✓	basic	1.36693e10 → 1.367e10
DarkMatterConcentration[2]	Concentration of dark matter particles assuming an NFW profile. Minimum particle radius set to softening length	1	float32	dimensionless	×	×	×	×	✓	basic	1.36693e10 → 1.367e10
DarkMatterConcentrationUnsoftened	Concentration of dark matter particles assuming an NFW profile. No particle softening	1	float32	dimensionless	×	×	×	×	✓	basic	1.36693e10 → 1.367e10

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
DarkMatterMass	1	float32	M	✓	✓	✓	✓	✓	basic	1.36693e10 → 1.367e10
Total DM mass.										
EncloseRadius	1	float32	a · L	✓	×	×	×	×	basic	1.36693e10 → 1.367e10
Radius of the particle furthest from the halo centre										
GasMass	1	float32	M	✓	✓	✓	✓	✓	basic	1.36693e10 → 1.367e10
Total gas mass.										
GasMassFractionInMetals[3]	1	float32	dimensionless	✓	✓	✓	×	✓	basic	1.36693e10 → 1.367e10
Total gas mass fraction in metals.										
HalfMassRadiusStars[4]	1	float32	a · L	✓	✓	✓	✓	×	basic	1.36693e10 → 1.367e10
Stellar half mass radius.										
MaximumCircularVelocity[5]	1	float32	L/t	✓	×	×	×	×	basic	1.36693e10 → 1.367e10
Maximum circular velocity when accounting for particle softening lengths.										
MaximumCircularVelocityRadiusUnsoftened[5]	1	float32	a · L	✓	×	×	×	×	basic	1.36693e10 → 1.367e10
Radius at which MaximumCircularVelocityUnsoftened is reached.										
MaximumCircularVelocityUnsoftened[5]	1	float32	L/t	✓	×	×	×	×	basic	1.36693e10 → 1.367e10
Maximum circular velocity when not accounting for particle softening lengths.										

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
MostMassiveBlackHoleID ID of most massive black hole.	1	uint64	dimensionless	✓	✓	✓	✓	✓	basic	Store less bits
MostMassiveBlackHoleMass[6] Mass of most massive black hole.	1	float32	M	✓	✓	✓	✓	✓	basic	1.36693e10 → 1.367e10
NoiseSuppressedNeutrinoMass[7] Noise suppressed total neutrino mass.	1	float32	M	×	×	×	×	✓	basic	1.36693e10 → 1.367e10
NumberOfBlackHoleParticles Number of black hole particles.	1	uint32	dimensionless	✓	✓	✓	✓	✓	basic	no compression
NumberOfDarkMatterParticles Number of dark matter particles.	1	uint32	dimensionless	✓	✓	✓	✓	✓	basic	no compression
NumberOfGasParticles Number of gas particles.	1	uint32	dimensionless	✓	✓	✓	✓	✓	basic	no compression
NumberOfNeutrinoParticles Number of neutrino particles.	1	uint32	dimensionless	×	×	×	×	✓	basic	no compression
NumberOfStarParticles Number of star particles.	1	uint32	dimensionless	✓	✓	✓	✓	✓	basic	no compression
RawNeutrinoMass[7] Total neutrino particle mass.	1	float32	M	×	×	×	×	✓	basic	1.36693e10 → 1.367e10

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
SORadius Radius of a sphere satisfying a spherical overdensity criterion.	1	float32	$a \cdot L$	✗	✗	✗	✗	✓	basic	1.36693e10 → 1.367e10
StarFormationRate[8] Total star formation rate.	1	float32	M/t	✓	✓	✓	✓	✓	basic	1.36693e10 → 1.367e10
StarFormingGasMassFractionInMetals[8,3] Total gas mass fraction in metals for gas that is star-forming.	1	float32	dimensionless	✓	✓	✓	✗	✓	basic	1.36693e10 → 1.367e10
StellarMass Total stellar mass.	1	float32	M	✓	✓	✓	✓	✓	basic	1.36693e10 → 1.367e10
StellarMassFractionInMetals Total stellar mass fraction in metals.	1	float32	dimensionless	✓	✓	✓	✗	✓	basic	1.36693e10 → 1.367e10
TotalMass Total mass.	1	float32	M	✓	✓	✓	✓	✓	basic	1.36693e10 → 1.367e10
BlackHolesLastEventScalefactor Scale-factor of last AGN event.	1	float32	dimensionless	✓	✓	✓	✓	✓	general	1.36693e10 → 1.367e10
ComptonY[9] Total Compton y parameter.	1	float64	L^2	✗	✗	✗	✗	✓	general	1.36693e10 → 1.367e10

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
ComptonYWithoutRecentAGNHeating[9] Total Compton y parameter. Excludes gas that was recently heated by AGN.	1	float64	L^2	✗	✗	✗	✗	✓	general	1.36693e10 → 1.367e10
DopplerB[10] Kinetic Sunyaey-Zel'dovich effect, assuming a line of sight towards the position of the first lightcone observer.	1	float32	a·	✗	✗	✗	✗	✓	general	1.36693e10 → 1.367e10
GasComptonYTemperature[11] ComptonY-weighted mean gas temperature.	1	float32	T	✗	✗	✗	✗	✓	general	1.36693e10 → 1.367e10
GasComptonYTemperatureCoreExcision[12,11] ComptonY-weighted mean gas temperature, excluding the inner excised core.	1	float32	T	✗	✗	✗	✗	✓	general	1.36693e10 → 1.367e10
GasComptonYTemperatureWithoutRecentAGNHeating[11] ComptonY-weighted mean gas temperature, excluding gas that was recently heated by AGN.	1	float32	T	✗	✗	✗	✗	✓	general	1.36693e10 → 1.367e10
GasComptonYTemperatureWithoutRecentAGNHeatingCoreExcision[12,11] ComptonY-weighted mean gas temperature, excluding the inner excised core and gas that was recently heated by AGN.	1	float32	T	✗	✗	✗	✗	✓	general	1.36693e10 → 1.367e10

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
GasMassFractionInIron[3] Total gas mass fraction in iron.	1	float32	dimensionless	×	✓	✓	×	✓	general	1.36693e10 → 1.367e10
GasMassFractionInOxygen[3] Total gas mass in oxygen.	1	float32	dimensionless	×	✓	✓	×	✓	general	1.36693e10 → 1.367e10
GasTemperature[13] Mass-weighted mean gas temperature.	1	float32	T	✓	✓	✓	×	✓	general	1.36693e10 → 1.367e10
GasTemperatureCoreExcision[12] Mass-weighted mean gas temperature, excluding the inner excised core.	1	float32	T	×	×	×	×	✓	general	1.36693e10 → 1.367e10
GasTemperatureWithoutCoolGas[13] Mass-weighted mean gas temperature, excluding cool gas with a temperature below 1e5 K.	1	float32	T	✓	×	×	×	✓	general	1.36693e10 → 1.367e10
GasTemperatureWithoutCoolGasAndRecentAGNHeating[13] Mass-weighted mean gas temperature, excluding cool gas with a temperature below 1e5 K and gas that was recently heated by AGN.	1	float32	T	✓	×	×	×	✓	general	1.36693e10 → 1.367e10
GasTemperatureWithoutCoolGasAndRecentAGNHeatingCoreExcision[12] Mass-weighted mean gas temperature, excluding the inner excised core, gas below 1e5 K and gas that was recently heated by AGN.	1	float32	T	×	×	×	×	✓	general	1.36693e10 → 1.367e10

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
GasTemperatureWithoutCoolGasCoreExcision[12] Mass-weighted mean gas temperature, excluding the inner excised core and gas below 1e5 K.	1	float32	T	×	×	×	×	✓	general	1.36693e10 → 1.367e10
GasTemperatureWithoutRecentAGNHeating[13] Mass-weighted mean gas temperature, excluding gas that was recently heated by AGN.	1	float32	T	✓	✓	✓	×	✓	general	1.36693e10 → 1.367e10
GasTemperatureWithoutRecentAGNHeatingCoreExcision[12] Mass-weighted mean gas temperature, excluding the inner excised core, and gas that was recently heated by AGN.	1	float32	T	×	×	×	×	✓	general	1.36693e10 → 1.367e10
HalfMassRadiusTotal[4] Total half mass radius.	1	float32	$a \cdot L$	✓	×	×	×	×	general	1.36693e10 → 1.367e10
HotGasMass Total mass of gas with a temperature above 1e5 K.	1	float32	M	×	×	×	×	✓	general	1.36693e10 → 1.367e10
MassFractionExternal[14] Fraction of mass that is bound to a satellite outside this FOF group.	1	float32	dimensionless	×	×	×	×	✓	general	1.36693e10 → 1.367e10
MassFractionSatellites[14] Fraction of mass that is bound to a satellite in the same FOF group.	1	float32	dimensionless	×	×	×	×	✓	general	1.36693e10 → 1.367e10

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
MostMassiveBlackHoleAccretionRate	1	float32	M/t	✓	✓	✓	×	✓	general	1.36693e10 → 1.367e10
Gas accretion rate of most massive black hole.										
MostMassiveBlackHoleLastEventScalefactor	1	float32	dimensionless	✓	✓	✓	✓	✓	general	1.36693e10 → 1.367e10
Scale-factor of last AGN event for most massive black hole.										
MostMassiveBlackHolePosition	3	float64	$a \cdot L$	✓	✓	✓	✓	✓	general	1 pc accurate
Position of most massive black hole.										
MostMassiveBlackHoleVelocity	3	float32	$a \cdot L/t$	✓	✓	✓	✓	✓	general	1.36693e10 → 1.367e10
Velocity of most massive black hole relative to the simulation volume.										
ProjectedTotalInertiaTensorNoniterative	3	float32	L^2	×	×	×	✓	×	general	1.36693e10 → 1.367e10
2D inertia tensor computed in a single iteration from the total mass distribution, relative to the halo centre. Diagonal components and one off-diagonal value as (1,1), (2,2), (1,2). Only calculated when we have more than 20 particles.										
ProjectedTotalInertiaTensorReducedNoniterative	3	float32	dimensionless	×	×	×	✓	×	general	1.36693e10 → 1.367e10
Reduced 2D inertia tensor computed in a single iteration from the total mass distribution, relative to the halo centre. Diagonal components and one off-diagonal value as (1,1), (2,2), (1,2). Only calculated when we have more than 20 particles.										

Name	Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
SpectroscopicLikeTemperature[15]	Spectroscopic-like gas temperature.	1	float32	T	✗	✗	✗	✗	✓	general	1.36693e10 → 1.367e10
SpectroscopicLikeTemperatureCoreExcision[12,15]	Spectroscopic-like gas temperature. Excludes gas in the inner excised core	1	float32	T	✗	✗	✗	✗	✓	general	1.36693e10 → 1.367e10
SpectroscopicLikeTemperatureWithoutRecentAGNHeating[15]	Spectroscopic-like gas temperature. Exclude gas that was recently heated by AGN	1	float32	T	✗	✗	✗	✗	✓	general	1.36693e10 → 1.367e10
SpectroscopicLikeTemperatureWithoutRecentAGNHeatingCoreExcision[12,15]	Spectroscopic-like gas temperature. Exclude gas that was recently heated by AGN. Excludes gas in the inner excised core	1	float32	T	✗	✗	✗	✗	✓	general	1.36693e10 → 1.367e10
SpinParameter[16]	Bullock et al. (2001) spin parameter.	1	float32	dimensionless	✓	✓	✓	✗	✓	general	1.36693e10 → 1.367e10
StarFormingGasMass[8]	Total mass of star-forming gas.	1	float32	M	✓	✓	✓	✗	✗	general	1.36693e10 → 1.367e10
StarFormingGasMassFractionInIron[8,3]	Total gas mass fraction in iron for gas that is star-forming.	1	float32	dimensionless	✗	✓	✓	✗	✗	general	1.36693e10 → 1.367e10

<table>
<tr><th>Name
Description</th><th>Shape</th><th>Type</th><th>Units</th><th>SH</th><th>ES</th><th>IS</th><th>EP</th><th>SO</th><th>Category</th><th>Compression</th></tr>
<tr><td>StarFormingGasMassFractionInOxygen[8,3]</td><td>1</td><td>float32</td><td>dimensionless</td><td>×</td><td>✓</td><td>✓</td><td>×</td><td>×</td><td>general</td><td>1.36693e10 → 1.367e10</td></tr>
<tr><td colspan="11">Total gas mass fraction in oxygen for gas that is star-forming.</td></tr>
<tr><td>ThermalEnergyGas[17]</td><td>1</td><td>float64</td><td>$\frac{L^2 \cdot M}{t^2}$</td><td>×</td><td>×</td><td>×</td><td>×</td><td>✓</td><td>general</td><td>1.36693e10 → 1.367e10</td></tr>
<tr><td colspan="11">Total thermal energy of the gas.</td></tr>
<tr><td>TotalInertiaTensor</td><td>6</td><td>float32</td><td>L^2</td><td>✓</td><td>×</td><td>×</td><td>×</td><td>×</td><td>general</td><td>1.36693e10 → 1.367e10</td></tr>
<tr><td colspan="11">3D inertia tensor computed iteratively from the total mass distribution, relative to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.</td></tr>
<tr><td>TotalInertiaTensorNoniterative</td><td>6</td><td>float32</td><td>L^2</td><td>✓</td><td>×</td><td>×</td><td>×</td><td>✓</td><td>general</td><td>1.36693e10 → 1.367e10</td></tr>
<tr><td colspan="11">3D inertia tensor computed in a single iteration from the total mass distribution, relative to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.</td></tr>
<tr><td>TotalInertiaTensorReduced</td><td>6</td><td>float32</td><td>dimensionless</td><td>✓</td><td>×</td><td>×</td><td>×</td><td>×</td><td>general</td><td>1.36693e10 → 1.367e10</td></tr>
<tr><td colspan="11">Reduced 3D inertia tensor computed iteratively from the total mass distribution, relative to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.</td></tr>
</table>

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
TotalInertiaTensorReducedNoniterative Reduced 3D inertia tensor computed in a single iteration from the total mass distribution, relative to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.	6	float32	dimensionless	✓	×	×	×	✓	general	1.36693e10 → 1.367e10
XRayLuminosity[18] Total observer-frame Xray luminosity in three bands.	3	float64	$\frac{L^2 \cdot M}{t^3}$	×	×	×	×	✓	general	1.36693e10 → 1.367e10
XRayLuminosityCoreExcision[12] Total observer-frame Xray luminosity in three bands. Excludes gas in the inner excised core	3	float64	$\frac{L^2 \cdot M}{t^3}$	×	×	×	×	✓	general	1.36693e10 → 1.367e10
XRayLuminosityInRestframe[18] Total rest-frame Xray luminosity in three bands.	3	float64	$\frac{L^2 \cdot M}{t^3}$	×	×	×	×	✓	general	1.36693e10 → 1.367e10
XRayLuminosityInRestframeCoreExcision Total rest-frame Xray luminosity in three bands. Excludes gas in the inner excised core	3	float64	$\frac{L^2 \cdot M}{t^3}$	×	×	×	×	✓	general	1.36693e10 → 1.367e10
XRayLuminosityInRestframeWithoutRecentAGNHeating Total rest-frame Xray luminosity in three bands. Excludes gas that was recently heated by AGN.	3	float64	$\frac{L^2 \cdot M}{t^3}$	×	×	×	×	✓	general	1.36693e10 → 1.367e10

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
XRayLuminosityInRestframeWithoutRecentAGNHeatingCoreExcision Total rest-frame Xray luminosity in three bands. Excludes gas that was recently heated by AGN. Excludes gas in the inner excised core	3	float64	$\frac{L^2 \cdot M}{t^3}$	×	×	×	×	✓	general	1.36693e10 → 1.367e10
XRayLuminosityWithoutRecentAGNHeating Total observer-frame Xray luminosity in three bands. Excludes gas that was recently heated by AGN.	3	float64	$\frac{L^2 \cdot M}{t^3}$	×	×	×	×	✓	general	1.36693e10 → 1.367e10
XRayLuminosityWithoutRecentAGNHeatingCoreExcision[12] Total observer-frame Xray luminosity in three bands. Excludes gas that was recently heated by AGN. Excludes gas in the inner excised core	3	float64	$\frac{L^2 \cdot M}{t^3}$	×	×	×	×	✓	general	1.36693e10 → 1.367e10
XRayPhotonLuminosity[18] Total observer-frame Xray photon luminosity in three bands.	3	float64	1/t	×	×	×	×	✓	general	1.36693e10 → 1.367e10
XRayPhotonLuminosityCoreExcision[12] Total observer-frame Xray photon luminosity in three bands. Excludes gas in the inner excised core	3	float64	1/t	×	×	×	×	✓	general	1.36693e10 → 1.367e10

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
XRayPhotonLuminosityInRestframe[18] Total rest-frame Xray photon luminosity in three bands.	3	float64	1/t	✗	✗	✗	✗	✓	general	1.36693e10 → 1.367e10
XRayPhotonLuminosityInRestframeCoreExcision Total rest-frame Xray photon luminosity in three bands. Excludes gas in the inner excised core	3	float64	1/t	✗	✗	✗	✗	✓	general	1.36693e10 → 1.367e10
XRayPhotonLuminosityInRestframeWithoutRecentAGNHeating Total rest-frame Xray photon luminosity in three bands. Exclude gas that was recently heated by AGN.	3	float64	1/t	✗	✗	✗	✗	✓	general	1.36693e10 → 1.367e10
XRayPhotonLuminosityInRestframeWithoutRecentAGNHeatingCoreExcision Total rest-frame Xray photon luminosity in three bands. Exclude gas that was recently heated by AGN. Excludes gas in the inner excised core	3	float64	1/t	✗	✗	✗	✗	✓	general	1.36693e10 → 1.367e10
XRayPhotonLuminosityWithoutRecentAGNHeating Total observer-frame Xray photon luminosity in three bands. Exclude gas that was recently heated by AGN.	3	float64	1/t	✗	✗	✗	✗	✓	general	1.36693e10 → 1.367e10

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
XRayPhotonLuminosityWithoutRecentAGNHeatingCoreExcision[12] Total observer-frame Xray photon luminosity in three bands. Exclude gas that was recently heated by AGN. Excludes gas in the inner excised core	3	float64	1/t	×	×	×	×	✓	general	1.36693e10 → 1.367e10
AngularMomentumGas[19] Total angular momentum of the gas, relative to the centre of potential and gas centre of mass velocity.	3	float32	$L^2 \cdot M/t$	✓	✓	✓	×	✓	gas	1.36693e10 → 1.367e10
DiscToTotalGasMassFraction Fraction of the total gas mass that is co-rotating.	1	float32	dimensionless	✓	✓	✓	×	✓	gas	1.36693e10 → 1.367e10
GasCentreOfMass Centre of mass of gas.	3	float64	$a \cdot L$	×	×	×	×	✓	gas	1 pc accurate
GasCentreOfMassVelocity Centre of mass velocity of gas.	3	float32	$a \cdot L/t$	×	×	×	×	✓	gas	0.1 km/s accurate
GasInertiaTensor 3D inertia tensor computed iteratively from the gas mass distribution, relative to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.	6	float32	L^2	✓	×	×	×	×	gas	1.36693e10 → 1.367e10

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
GasInertiaTensorNoniterative 3D inertia tensor computed in a single iteration from the gas mass distribution, relative to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.	6	float32	L^2	✓	✗	✗	✗	✓	gas	1.36693e10 → 1.367e10
GasInertiaTensorReduced Reduced 3D inertia tensor computed iteratively from the gas mass distribution, relative to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.	6	float32	dimensionless	✓	✗	✗	✗	✗	gas	1.36693e10 → 1.367e10
GasInertiaTensorReduced-Noniterative Reduced 3D inertia tensor computed in a single iteration from the gas mass distribution, relative to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.	6	float32	dimensionless	✓	✗	✗	✗	✓	gas	1.36693e10 → 1.367e10
GasProjectedVelocityDispersion[20] Mass-weighted velocity dispersion of the gas along the projection axis, relative to the gas centre of mass velocity.	1	float32	L/t	✗	✗	✗	✓	✗	gas	1.36693e10 → 1.367e10
GasVelocityDispersionMatrix[21] Mass-weighted velocity dispersion of the gas. Measured relative to the gas centre of mass velocity. The order of the components of the dispersion tensor is XX YY ZZ XY XZ YZ.	6	float32	$\frac{L^2}{t^2}$	✓	✗	✗	✗	✗	gas	1.36693e10 → 1.367e10
HalfMassRadiusGas[4] Gas half mass radius.	1	float32	$a \cdot L$	✓	✓	✓	✓	✗	gas	1.36693e10 → 1.367e10

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
KappaCorotGas[22]	1	float32	dimensionless	✓	✓	✓	×	×	gas	1.36693e10 → 1.367e10
Kappa-corot for gas, relative to the centre of potential and the centre of mass velocity of the gas.										
KineticEnergyGas[23]	1	float64	$\frac{L^2 \cdot M}{t^2}$	×	✓	✓	×	✓	gas	1.36693e10 → 1.367e10
Total kinetic energy of the gas, relative to the gas centre of mass velocity.										
ProjectedGasInertiaTensor-Noniterative	3	float32	L^2	×	×	×	✓	×	gas	1.36693e10 → 1.367e10
2D inertia tensor computed in a single iteration from the gas mass distribution, relative to the halo centre. Diagonal components and one off-diagonal value as (1,1), (2,2), (1,2). Only calculated when we have more than 20 particles.										
ProjectedGasInertiaTensor-ReducedNoniterative	3	float32	dimensionless	×	×	×	✓	×	gas	1.36693e10 → 1.367e10
Reduced 2D inertia tensor computed in a single iteration from the gas mass distribution, relative to the halo centre. Diagonal components and one off-diagonal value as (1,1), (2,2), (1,2). Only calculated when we have more than 20 particles.										
AngularMomentumDarkMatter[19]	3	float32	$L^2 \cdot M/t$	✓	✓	✓	×	✓	dm	1.36693e10 → 1.367e10
Total angular momentum of the dark matter, relative to the centre of potential and DM centre of mass velocity.										

Name	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression	Description
DarkMatterInertiaTensor	6	float32	L^2	✓	×	×	×	×	dm	1.36693e10 → 1.367e10	3D inertia tensor computed iteratively from the DM mass distribution, relative to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.
DarkMatterInertiaTensorNoniterative	6	float32	L^2	✓	×	×	×	✓	dm	1.36693e10 → 1.367e10	3D inertia tensor computed in a single interation from the DM mass distribution, relative to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.
DarkMatterInertiaTensorReduced	6	float32	dimensionless	✓	×	×	×	×	dm	1.36693e10 → 1.367e10	Reduced 3D inertia tensor computed iteratively from the DM mass distribution, relative to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.
DarkMatterInertiaTensorReducedNoniterative	6	float32	dimensionless	✓	×	×	×	✓	dm	1.36693e10 → 1.367e10	Reduced 3D inertia tensor computed in a single interation from the DM mass distribution, relative to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.
DarkMatterProjectedVelocityDispersion[20]	1	float32	L/t	×	×	×	✓	×	dm	1.36693e10 → 1.367e10	Mass-weighted velocity dispersion of the DM along the projection axis, relative to the DM centre of mass velocity.

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
DarkMatterVelocityDispersionMatrix[21] Mass-weighted velocity dispersion of the dark matter. Measured relative to the DM centre of mass velocity. The order of the components of the dispersion tensor is XX YY ZZ XY XZ YZ.	6	float32	$\frac{L^2}{t^2}$	✓	×	×	×	×	dm	1.36693e10 → 1.367e10
HalfMassRadiusDarkMatter[4] Dark matter half mass radius.	1	float32	$a \cdot L$	✓	✓	✓	✓	×	dm	1.36693e10 → 1.367e10
MaximumDarkMatterCircularVelocity Maximum circular velocity calculated using dark matter particles when accounting for particle softening lengths..	1	float32	L/t	✓	×	×	×	×	dm	1.36693e10 → 1.367e10
MaximumDarkMatterCircularVelocityRadius Radius at which MaximumDarkMatterCircularVelocity is reached.	1	float32	$a \cdot L$	✓	×	×	×	×	dm	1.36693e10 → 1.367e10
AngularMomentumStars[19] Total angular momentum of the stars, relative to the centre of potential and stellar centre of mass velocity.	3	float32	$L^2 \cdot M/t$	✓	✓	✓	×	✓	star	1.36693e10 → 1.367e10
DiscToTotalStellarMassFraction Fraction of the total stellar mass that is co-rotating.	1	float32	dimensionless	✓	✓	✓	×	✓	star	1.36693e10 → 1.367e10

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
KappaCorotStars[22]	1	float32	dimensionless	✓	✓	✓	✗	✗	star	1.36693e10 → 1.367e10
Kappa-corot for stars, relative to the centre of potential and the centre of mass velocity of the stars.										
KineticEnergyStars[23]	1	float64	$\frac{L^2 \cdot M}{t^2}$	✗	✓	✓	✗	✓	star	1.36693e10 → 1.367e10
Total kinetic energy of the stars, relative to the stellar centre of mass velocity.										
LuminosityWeightedMeanStellarAge	1	float32	t	✓	✓	✓	✗	✗	star	1.36693e10 → 1.367e10
Luminosity weighted mean stellar age. The weight is the r band luminosity.										
MassWeightedMeanStellarAge	1	float32	t	✓	✓	✓	✗	✗	star	1.36693e10 → 1.367e10
Mass weighted mean stellar age.										
ProjectedStellarInertiaTensorNoniterative	3	float32	L^2	✗	✗	✗	✓	✗	star	1.36693e10 → 1.367e10
2D inertia tensor computed in a single iteration from the stellar mass distribution, relative to the halo centre. Diagonal components and one off-diagonal value as (1,1), (2,2), (1,2). Only calculated when we have more than 20 particles.										
ProjectedStellarInertiaTensorReducedNoniterative	3	float32	dimensionless	✗	✗	✗	✓	✗	star	1.36693e10 → 1.367e10
Reduced 2D inertia tensor computed in a single iteration from the stellar mass distribution, relative to the halo centre. Diagonal components and one off-diagonal value as (1,1), (2,2), (1,2). Only calculated when we have more than 20 particles.										

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
StellarCentreOfMass Centre of mass of stars.	3	float64	$a \cdot L$	×	✓	✓	×	✓	star	1 pc accurate
StellarCentreOfMassVelocity Centre of mass velocity of stars.	3	float32	$a \cdot L/t$	×	✓	✓	×	✓	star	0.1 km/s accurate
StellarInertiaTensor 3D inertia tensor computed iteratively from the stellar mass distribution, relative to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.	6	float32	L^2	✓	×	×	×	×	star	1.36693e10 → 1.367e10
StellarInertiaTensorNoniterative 3D inertia tensor computed in a single iteration from the stellar mass distribution, relative to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.	6	float32	L^2	✓	×	×	×	✓	star	1.36693e10 → 1.367e10
StellarInertiaTensorReduced Reduced 3D inertia tensor computed iteratively from the stellar mass distribution, relative to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.	6	float32	dimensionless	✓	×	×	×	×	star	1.36693e10 → 1.367e10
StellarInertiaTensorReduced-Noniterative Reduced 3D inertia tensor computed in a single iteration from the stellar mass distribution, relative to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.	6	float32	dimensionless	✓	×	×	×	✓	star	1.36693e10 → 1.367e10

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
StellarInitialMass Total stellar initial mass.	1	float32	M	✓	✓	✓	✓	✓	star	1.36693e10 → 1.367e10
StellarLuminosity[24] Total stellar luminosity in the 9 GAMA bands.	9	float32	dimensionless	✓	✓	✓	✓	✓	star	1.36693e10 → 1.367e10
StellarMassFractionInIron Total stellar mass fraction in iron.	1	float32	dimensionless	×	✓	✓	×	✓	star	1.36693e10 → 1.367e10
StellarMassFractionInOxygen Total stellar mass fraction in oxygen.	1	float32	dimensionless	×	✓	✓	×	✓	star	1.36693e10 → 1.367e10
StellarProjectedVelocityDispersion[20] Mass-weighted velocity dispersion of the stars along the projection axis, relative to the stellar centre of mass velocity.	1	float32	L/t	×	×	×	✓	×	star	1.36693e10 → 1.367e10
StellarVelocityDispersionMatrix[21] Mass-weighted velocity dispersion of the stars. Measured relative to the stellar centre of mass velocity. The order of the components of the dispersion tensor is XX YY ZZ XY XZ YZ.	6	float32	$\frac{L^2}{t^2}$	✓	×	×	×	×	star	1.36693e10 → 1.367e10
AngularMomentumBaryons[19] Total angular momentum of baryons (gas and stars), relative to the centre of potential and baryonic centre of mass velocity.	3	float32	$L^2 \cdot M/t$	✓	✓	✓	×	✓	baryon	1.36693e10 → 1.367e10
HalfMassRadiusBaryons Baryonic (gas and stars) half mass radius.	1	float32	$a \cdot L$	✓	✓	✓	✓	×	baryon	1.36693e10 → 1.367e10

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
KappaCorotBaryons[22]	1	float32	dimensionless	✓	✓	✓	×	×	baryon	1.36693e10 → 1.367e10
Kappa-corot for baryons (gas and stars), relative to the centre of potential and the centre of mass velocity of the baryons.										
HaloCatalogueIndex	1	int64	dimensionless	×	×	×	×	×	Input	no compression
Index of this halo in the original halo finder catalogue (first halo has index=0).										
HaloCentre	3	float64	$a \cdot L$	×	×	×	×	×	Input	1 pc accurate
The centre of the subhalo as given by the halo finder. Used as reference for all relative positions. For VR and HBTplus this is equal to the position of the most bound particle in the subhalo.										
IsCentral	1	int64	dimensionless	×	×	×	×	×	Input	no compression
Whether the halo finder flagged the halo as central (1) or satellite (0).										
NumberOfBoundParticles	1	int64	dimensionless	×	×	×	×	×	Input	no compression
Total number of particles bound to the subhalo.										
Depth	1	uint64	dimensionless	×	×	×	×	×	HBTplus	no compression
Level of the subhalo in the merging hierarchy.										
DescendantTrackId	1	int64	dimensionless	×	×	×	×	×	HBTplus	no compression
TrackId of the descendant of this subhalo.										
HostFOFId	1	int64	dimensionless	×	×	×	×	×	HBTplus	no compression
ID of the host FOF halo of this subhalo. Hostless halos have HostFOFId == -1										

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
LastMaxMass Maximum mass of this subhalo across its evolutionary history	1	float32	M	×	×	×	×	×	HBTplus	1.36693e10 → 1.367e10
LastMaxVmaxPhysical Largest value of maximum circular velocity of this subhalo across its evolutionary history	1	float32	L/t	×	×	×	×	×	HBTplus	1.36693e10 → 1.367e10
NestedParentTrackId TrackId of the parent of this subhalo.	1	int64	dimensionless	×	×	×	×	×	HBTplus	no compression
SnapshotIndexOfBirth Snapshot when this subhalo was formed.	1	int64	dimensionless	×	×	×	×	×	HBTplus	no compression
SnapshotIndexOfLastMaxMass Latest snapshot when this subhalo had its maximum mass.	1	uint64	dimensionless	×	×	×	×	×	HBTplus	no compression
SnapshotIndexOfLastMaxVmax Latest snapshot when this subhalo had its largest maximum circular velocity.	1	uint64	dimensionless	×	×	×	×	×	HBTplus	no compression
TrackId Unique ID for this subhalo which is consistent across snapshots.	1	uint64	dimensionless	×	×	×	×	×	HBTplus	no compression
Centres Centre of mass of the host FOF halo of this subhalo. Zero for satellite and hostless subhalos.	3	float64	$a \cdot L$	×	×	×	×	×	FOF	1 pc accurate
Masses Mass of the host FOF halo of this subhalo. Zero for satellite and hostless subhalos.	1	float32	M	×	×	×	×	×	FOF	1.36693e10 → 1.367e10

Name	Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
Sizes	Number of particles in the host FOF halo of this subhalo. Zero for satellite and hostless subhalos.	1	uint64	dimensionless	×	×	×	×	×	FOF	no compression
HostHaloIndex	Index (within the SOAP arrays) of the top level parent of this subhalo. -1 for central subhalos.	1	int64	dimensionless	×	×	×	×	×	SOAP	no compression
IncludedInReducedSnapshot	Whether this halo is included in the reduced snapshot.	1	int32	dimensionless	×	×	×	×	×	SOAP	no compression
SubhaloRankByBoundMass	Ranking by mass of the halo within its parent field halo. Zero for the most massive halo in the field halo.	1	int32	dimensionless	×	×	×	×	×	SOAP	no compression

5 Non-trivial properties

^{1}**The centre of mass and centre of mass velocity** are computed using all particle types except neutrinos (since neutrinos can never be bound to a halo).

^{2}**The concentration** is computed using the method described in Wang et al. (2023), but using a fifth order polynomial fit to the R1-concentration relation for $1 < c < 1000$. Therefore we set a floor of 1 and a ceiling of 1000 for the values calculated by SOAP. This method assumes halos have an NFW profile, and is only calculated for the following SO variations: 200_{crit}, 200_{mean}, and $BN98$. Neutrinos are included in the calculation of total concentration. The first moment of the density distribution, $R1$, can be estimated from the concentration. From $R1$ the Einasto concentration can be calculated. It also possible to estimate other properties, such as V_{max}, by using the $R1$ value and assuming an NFW profile.

^{3}**The oxygen and iron masses** are computed from `SmoothedElementMassFractions` and not `ElementMassFractions`, since the latter were not output in the FLAMINGO snapshots. Metal mass fractions on the other hand are based on `MetalMassFractions`.

^{4}**The half mass radius** is determined from linear interpolation of the cumulative mass profile obtained after sorting all particles by radius. For the projected halos (PA), SOAP uses the 2D radius (distance to the projection axis) instead of the 3D radius.

^{5}**The maximum circular velocity and the radius where it is reached** are computed using

$$v_{\rm max} = \sqrt{\frac{GM(\leq r)}{r}}, \tag{1}$$

where the cumulative mass $M(\leq r)$ includes all particles within the radius r, and includes the contribution of the particle(s) at $r = 0$. The radius is computed relative to the centre of potential. The softened $v_{\rm max}$ value is calculated using the same method, except the particle radius has a floor of the softening length. An alternative way to calculate $v_{\rm max}$ is to estimate it from the halo concentration by assuming an NFW profile. We store the radius of the unsoftened maximum circular velocity. If the softened and unsoftened maximum circular velocities are equal, then their radii will also be equal. If the values are not equal, then the radius of the softened maximum circular velocity will be the simulation softening length.

^{6}**The most massive black hole** is identified based on the BH subgrid mass (i.e. the same mass that goes into `BlackHolesSubgridMass`).

[7]**The neutrino masses** exist in two flavours. `RawNeutrinoMass` is obtained by simply summing the neutrino particle masses, while the noise suppressed version, `NoiseSuppressedNeutrinoMass` is defined as

$$M_{\nu,\mathrm{NS}} = \sum_i m_i w_i + \frac{4\pi}{3}\rho_\nu R_{\mathrm{SO}}^3, \tag{2}$$

where w_i are the neutrino weights (which can be negative), and ρ_ν is the background density of neutrinos that is also used in the SO radius calculation. The latter is obtained from the snapshot header.

[8]**When distinguishing between star-forming and non star-forming gas and computing the total star formation rate,** we have to be careful about the interpretation of the `StarFormationRates` dataset in the snapshots, since negative values in that dataset are used to store another quantity, the last scale factor when that particular gas particle was star-forming. Star-forming gas is then gas for which `StarFormationRates` is strictly positive, and the total star formation rate is the sum of only the strictly positive values.

[9]**The Compton y parameter** is computed as in McCarthy et al. (2017):

$$y = \sum_i \frac{\sigma_T}{m_e c^2} n_{e,i} k_B T_{e,i} \frac{m_i}{\rho_i}, \tag{3}$$

where σ_T is the Thomson cross section, m_e the electron mass, c the speed of light and k_B the Boltzmann constant. $n_{e,i}$ and $T_{e,i}$ are the electron number density and electron temperature for gas particle i, while $V_i = m_i/\rho_i$ is the SPH volume element that turns the sum over all particles i within the inclusive sphere into a volume integral. Note that the snapshot already contains the individual y_i values for the SPH particles, computed from the cooling tables during the simulation.

[10]**The Doppler B parameter** is computed as in Roncarelli et al. (2018):

$$b = \frac{\sigma_T}{c} \sum_i n_{e,i} v_{r,\mathrm{obs},i} \frac{m_i}{\rho_i A_{\mathrm{obs}}}, \tag{4}$$

where σ_T is the Thomson cross section, c the speed of light, $n_{e,i}$ the electron number density for gas particle i, with $V_i = m_i/\rho_i$ the corresponding SPH particle volume. The relative *peculiar* velocity is taken relative to the box and along a line of sight towards a particular observer, so

$$v_{r,\mathrm{obs},i} = \vec{v}_i \cdot \frac{(\vec{x}_i - \vec{x}_{\mathrm{obs}})}{|\vec{x}_i - \vec{x}_{\mathrm{obs}}|}, \tag{5}$$

with $\vec{x}_i$ and $\vec{v}_i$ the physical position and velocity of particle i, and $\vec{x}_{\mathrm{obs}}$ the arbitrary observer position.

The surface area A_{obs} that turns the volume integral into a line integral is that of the aperture for which b is computed, i.e. $A_{\mathrm{obs}} = \pi R_{\mathrm{SO}}^2$.

As the observer position we use the position of the observer for the first lightcone in the simulation, or the centre of the box if no lightcone was present. This choice is arbitrary and can be adapted. Since $\vec{x}_{\mathrm{obs}}$ can in principle coincide with $\vec{x}_i$, we make sure $v_{r,\mathrm{obs},i}$ is set to zero in this case to avoid division by zero.

[11]**The Compton Y-weighted temperature** is computed as

$$T = \frac{1}{\sum_i y_i} \sum_i y_i T_i, \tag{6}$$

[12]**Core excised quantities** Excludes the inner region of the halo when computing the quantity. It is only calculated for `SO/500_crit`. Any core excised calculation only uses the particles for which

$$0.15 R_{500c} \leq \mathbf{r} \geq R_{500c} \tag{7}$$

[13]**The mass-weighted temperature** is computed as

$$T = \frac{1}{\sum_i m_i} \sum_i m_i T_i, \tag{8}$$

and the `GasTemperatureWithoutRecentAGNHeating` variant uses the same definition, but excludes particles that satisfy

$$\texttt{LastAGNFeedbackScaleFactors}_i \geq a - 15\mathrm{Myr} \tag{9}$$

and

$$0.1 \Delta T_{\mathrm{AGN}} \leq T_i \leq 10^{0.3} \Delta T_{\mathrm{AGN}}, \tag{10}$$

using the same parameters as used internally by SWIFT and with a the current scale factor.

[14]**The satellite mass fractions** is obtained by summing the masses of all particles within the inclusive sphere that are bound to a subhalo that is not the central subhalo, and dividing this by M_{SO}. This uses the same membership information that is also used to decide what particles need to be included in the exclusive sphere and projected aperture properties. For MassFractionSatellites we only consider particles with the same FOF ID as the most bound particle in the central subhalo. For MassFractionExternal we include all particles with a FOF ID not equal to the most bound particle in the central subhalo.

[15] **The spectroscopic-like temperature** is computed as

$$T_{SL} = \frac{\sum_i \rho_i m_i T_i^{1/4}}{\sum_i \rho_i m_i T_i^{-3/4}} \tag{11}$$

[16] **The spin parameter** is computed following Bullock et al. (2021):

$$\lambda = \frac{|\vec{L}_{\rm tot}|}{\sqrt{2} M v_{\rm max} R}, \tag{12}$$

where $\vec{L}_{\rm tot}$ is the total angular momentum of all particles within radius R, and M their total mass. The angular momentum is computed relative to the centre of potential and the total centre of mass velocity. Since subhalos do not have a natural radius associated with them, we use the radius where the softened $v_{\rm max}$ is reached.

[17] **The thermal energy** of the gas is computed from the density and pressure, since the internal energy was not output in the FLAMINGO snapshots. The relevant equation is

$$u = \frac{P}{(\gamma - 1)\rho}, \tag{13}$$

with $\gamma = 5/3$.

[18] **X-ray quantities are** computed directly from the X-ray datasets in the snapshot. They are either in the emission rest-frame, or in the observed-frame of a $z = 0$ observer, using the redshift of the snapshot as the emission redshift . The three bands are always given in the same order as in the snapshot:

1. eRosita low/soft ($0.2 - 2.3$ keV)
2. eRosita high/hard ($2.3 - 8$ keV)
3. ROSAT ($0.5 - 2$ keV)

[19] **The angular momentum** of gas, dark matter and stars is computed relative to the centre of potential (cop) and the centre of mass velocity of that particular component, and not to to the total centre of mass velocity. The full expression is

$$\vec{L}_{\rm comp} = \sum_{i={\rm comp}} m_i \left(\vec{x}_{r,i} \times \vec{v}_{{\rm comp},r,i} \right), \tag{14}$$

with the sum i over all particles of that particular component (bound to the halo), and

$$\vec{x}_{r,i} = \vec{x}_i - \vec{x}_{\rm cop}, \tag{15}$$

$$\vec{v}_{\mathrm{comp},r,i} = \vec{v}_i - \vec{v}_{\mathrm{com,comp}}, \tag{16}$$

where

$$\vec{v}_{\mathrm{com,comp}} = \frac{\sum_{i=\mathrm{comp}} m_i \vec{v}_i}{\sum_{i=\mathrm{comp}} m_i}. \tag{17}$$

For FLAMINGO, we also compute the angular momentum for baryons, where the sum is then over both gas and star particles.

^{20}**The projected velocity dispersion** is computed along the projection axis. Along this axis, the velocity is a 1D quantity, so that the velocity dispersion is simply 1 value.

^{21}**The velocity dispersion matrix** is defined as

$$V_{\mathrm{disp,comp}} = \frac{1}{\sum_{i=\mathrm{comp}} m_i} \sum_{i=\mathrm{comp}} m_i \vec{v}_{\mathrm{comp},r,i} \vec{v}_{\mathrm{comp},r,i}, \tag{18}$$

where we compute the relative velocity as before, i.e. w.r.t. the centre of mass velocity of the particular component of interest. While it is strictly speaking a 3×3 matrix, there are only 6 independent components. We use the following convention to output those 6 components as a 6 element array:

$$V'_{\mathrm{disp}} = \begin{pmatrix} V_{xx} & V_{yy} & V_{zz} & V_{xy} & V_{xz} & V_{yz} \end{pmatrix}. \tag{19}$$

Other velocity dispersion definitions can be derived from this general form. The one-dimensional velocity dispersion can be calculated as

$$\sigma = \sqrt{\frac{V_{xx} + V_{yy} + V_{zz}}{3}} \tag{20}$$

$^{22}\kappa_{\mathrm{corot}}$ is computed as in Correa et al. (2017):

$$\kappa_{\mathrm{corot,comp}} = \frac{K_{\mathrm{corot,comp}}}{K_{\mathrm{comp}}}, \tag{21}$$

with the kinetic energy given by

$$K_{\mathrm{comp}} = \frac{1}{2} \sum_{i=\mathrm{comp}} m_i |\vec{v}_{\mathrm{comp},r,i}|^2, \tag{22}$$

the corotational kinetic energy given by

$$K_{\mathrm{corot,comp}} = \sum_{i=\mathrm{comp}} \begin{cases} K_{\mathrm{rot,comp},i}, & L_{\mathrm{comp},p,i} > 0, \\ 0, & L_{\mathrm{comp},p,i} \leq 0, \end{cases} \tag{23}$$

the corotational kinetic energy given by

$$K_{\mathrm{corot,comp}} = \sum_{i=\mathrm{comp}} \begin{cases} K_{\mathrm{rot,comp},i}, & L_{\mathrm{comp},p,i} > 0, \\ 0, & L_{\mathrm{comp},p,i} \leq 0, \end{cases} \tag{24}$$

the rotational kinetic energy given by

$$K_{\mathrm{rot,comp},i} = \frac{1}{2} \frac{L^2_{\mathrm{comp},p,i}}{m_i R_i^2}, \tag{25}$$

the projected angular momentum along the angular momentum direction given by

$$L_{\mathrm{comp},p,i} = \vec{L}_i \frac{\vec{L}_{\mathrm{comp}}}{|\vec{L}_{\mathrm{comp}}|}, \tag{26}$$

and the orthogonal distance to the angular momentum vector given by

$$R_i^2 = |\vec{x}_{r,i}|^2 - \left(\vec{x}_{r,i} \frac{\vec{L}_{\mathrm{comp}}}{|\vec{L}_{\mathrm{comp}}|} \right), \tag{27}$$

where the angular momentum vector and the relative position and velocity are the same as above for consistency.

[23]**The kinetic energy** of the gas and stars is computed using the same relative velocities as used for other properties, i.e. relative to the centre of mass velocity of the gas and stars respectively.

[24]**Luminosities are given in the GAMA bands** and are always using the same order as in the snapshots: u, g, r, i, z, Y, J, H, K. These are rest-frame dust-free AB-luminosities of the star particles. These were computed using the BC03 (GALAXEV) models convolved with different filter bands and interpolated in log-log (f(log(Z), log(age)) = log(flux)) as used in the dust-free modelling of Trayford et al. (2015). The luminosities are given in dimensionless units. They have been divided by 3631 Jy already, i.e. they can be turned into absolute AB-magnitudes (rest-frame absolute maggies) directly by applying -2.5 log10(L) without additional corrections.

6 Spherical overdensity calculations

The radius at which the density reaches a certain threshold value is found by linear interpolation of the cumulative mass profile obtained after sorting the particles by radius. The approach we use is different from that taken by VR, where both the mass and the radius are obtained from independent interpolations on the mass and density profiles (the latter uses the logarithm of the density in the interpolation). The VR approach is inconsistent, in the sense that the condition

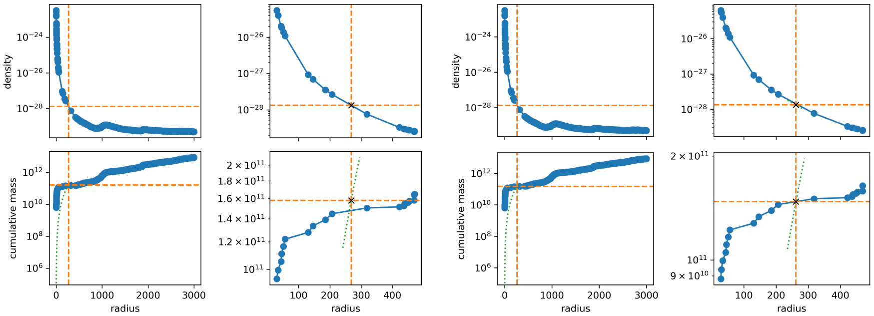

Figure 1: Density profile (*top row*) and cumulative mass profile (*bottom row*) for an example halo in a 400 Mpc FLAMINGO box. The orange lines show $\rho_{\rm target}$ and $R_{\rm SO}$ and $M_{\rm SO}$ as determined by SOAP, while the green line is the cumulative mass profile at fixed $\rho_{\rm target}$. The two left columns correspond to a run where $R_{\rm SO}$ is fixed by interpolating on the density profile (so in the top row plot), while the second two columns determine $R_{\rm SO}$ by interpolating on the cumulative mass in the bottom row plots. The right column for each pair of columns shows a zoom of the left column.

$$\frac{4\pi}{3} R_{\rm SO}^3 \rho_{\rm target} = M_{\rm SO}, \tag{28}$$

is not guaranteed to be true, and will be especially violated for large radial bins (the bins are generated from the particle radii by sorting the particles, so we have no control over their width). We instead opt to guarantee this condition by only finding $R_{\rm SO}$ or $M_{\rm SO}$ by interpolation and using eq. (28) to derive the other quantity.

While the interpolation of the logarithmic density profile to find $R_{\rm SO}$ is more straightforward, we found that it can lead to significant deviations between the value of $M_{\rm SO}$ and the cumulative mass in neighbouring bins that can be more than one particle mass, as illustrated in Fig. 1. The reason for this is that the cumulative mass profile at fixed density increases very steeply with radius, so that a small difference in $R_{\rm SO}$ leads to a relatively large difference in $M_{\rm SO}$. Conversely, fixing $M_{\rm SO}$ will lead to an $R_{\rm SO}$ that only deviates a little bit from the $R_{\rm SO}$ found by interpolating the density profile. However, doing so requires us to find the intersection of the cumulative mass profile at fixed density (green line in Fig. 1) with the actual cumulative mass profile, which means solving the following equation:

$$\frac{4\pi}{3} \rho_{\rm target} R_{\rm SO}^3 = M_{\rm low} + \left(\frac{M_{\rm high} - M_{\rm low}}{R_{\rm high} - R_{\rm low}} \right) \left(R_{\rm SO} - R_{\rm low} \right), \tag{29}$$

where $R/M_{\rm low/high}$ are the bounds of the intersecting bin (which we find in the density profile). This third degree polynomial equation has no unique solution, although in practice only one of the three possible complex solutions is real. We find this solution by using a root finding algorithm within the intersecting bin (we use Brent's method for this).

For clarity, this is the full set of rules for determining the SO radius in SOAP:

1. Sort particles according to radius and construct the cumulative mass profile.
2. Discard any particles at zero radius, since we cannot compute a density for those. The mass of these particles is used as an $r = 0$ offset for the cumulative mass profile. Since the centre of potential is the position of the most bound particle, there should always be at least one such particle.
3. Construct the density profile by dividing the cumulative mass at every radius by the volume of the sphere with that radius.
4. Find intersection points between the density profile and the target density, i.e. the radii $R_{1,2}$ and masses $M_{1,2}$ where the density profile goes from above to below the threshold:
   (a) If there are none, analytically compute $R_{\rm SO} = \sqrt{3M_1/(4\pi R_1 \rho_{\rm target})}$, where R_1 and M_1 are the first non zero radius and the corresponding cumulative mass. This is a special case of Eq. (29). Unless there are multiple particles at the exact centre of potential position, this radius estimate will then be based on just two particles.
   (b) In all other cases, we use $R_{1,2}$ and $M_{1,2}$ as input for Eq. (29) and solve for $R_{\rm SO}$. The only exception is the special case where $R_1 = R_2$. If that happens, we simply move further down the line until we find a suitable interval.
5. From $R_{\rm SO}$, we determine $M_{\rm SO}$ using Eq. (28).

Neutrinos – if present in the model – are included in the inclusive sphere calculation (and only here, since neutrino particles cannot be bound to a halo) by adding both their weighted masses (which can be negative), as well as the contribution from the background neutrino density. The latter is achieved by explicitly adding the cumulative mass profile at constant neutrino density to the total cumulative mass profile before computing the density profile. This is the only place where neutrinos explicitly enter the algorithm, except for the neutrino masses computed for the SOs. Neutrinos are not included in the calculation of the centre of mass and centre of mass velocity.

7 Group membership files

Before SOAP can be run we generate a set of files which contain halo membership information for each particle in the SWIFT snapshot. The datasets in these files are stored in the same order and with the same partitioning between files as the datasets in the snapshots. This allows SOAP to read halo membership information for sub-regions of the simulation volume without reading the full halo-finder output. These files may also be useful for visualising the input halo catalogue.

The group membership files are HDF5 files with one group for each particle type, named PartType0, PartType1, ... as in the snapshots. Each group contains the following datasets:

1. `GroupNr_bound`: for each particle in the corresponding snapshot file this contains the array index of the subhalo which the particle is bound to. If a particle is not bound to any subhalo it will have `GroupNr_bound`=-1.

2. `Rank_bound`: the ranking by total energy of this particle within the subhalo it belongs to, or -1 if the particle is not bound to any subhalo. The particle with the most negative total energy has `Rank_bound`=0.

3. `GroupNr_all`: (VELOCIraptor only) for each particle in the corresponding snapshot file this contains the array index of the VR group which the particle belongs to, regardless of whether it is bound or unbound. Particles in no group have `GroupNr_all`=-1.

4. `FOFGroupIDs`: the 3D FOF group the particle is part of. This field is only present if a FOF snapshot is listed in the parameter file. This field is present in the snapshots themselves, but for FLAMINGO hydro simulations the FOF was regenerated. If this field is present it will overwrite the value from the snapshots when SOAP is run.

The GroupNr values stored here are zero based array indexes into the full subhalo catalogue, and not the subhalos IDs. For example the first group in the VELOCIraptor catalogue has GroupNr=0 and ID=1.

The script ‘make_virtual_snapshot.py‘ will combine snapshot and group membership files into a single virtual snapshot file. This virtual file can be read by swiftsimio and gadgetviewer to provide halo membership information alongside other particle properties. Using the virtual file along with the spatial masking functionality within swiftsimio means it is possible to quickly load all the particles bound to a given subhalo.